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An Evaluation of Boundary Conditions for Modeling Urban Boundary Layers

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1. Introduction

Numerical modeling of the urban boundary layer is complicated by the need to describe airflow patterns outside of the computational domain. These patterns have an impact on how successfully the simulation is able to model the turbulence associated with the urban boundary layer. This talk presents experiments with the model boundary conditions for simulations that were done to support two Department of Energy observational programs involving the Salt Lake City basin. The Chemical/Biological Non-proliferation Program (CBNP) is concerned with the effects of buildings on influencing dispersion patterns in urban environments. The Vertical Transport and Mixing Program (VTMX) is investigating mixing mechanisms in the stable boundary layer and how they are influenced by the channeling caused by drainage flows or by obstacles such as building complexes. Both of these programs are investigating the turbulent mixing caused by building complexes and other urban obstacles.

2. Urban Scale Dispersion

Atmospheric dispersion in Salt Lake City is multi-scale in scope with drainage flows from the nearby mountains interacting with boundary layer motions whose scale is determined by surface obstacles. This investigation of urban boundary layer motions uses simulations of a fine scale turbulence model, FEM3MP (Finite Element Method Version 3 Massively Parallel), driven by wind and thermodynamic information taken from a mesoscale model, COAMPS (Coupled Oceanographic and Atmospheric Mesoscale Prediction System). This approach was chosen for its ability to perform both forecasting and assessment tasks. An example of this coupled modeling system is shown in Figures 1 and 2. Figure 1 shows three nested COAMPS domains with horizontal resolutions of 36, 12, and 4 km. The outermost nest contains the western half of the United states, while the finest nest is centered on Salt Lake City and contains the surrounding mountains and the Great Salt Lake. Figure 2 shows a fine scale FEM3MP simulation which was driven by a horizontally uniform inflow profile taken from the COAMPS simulation. The gray blocks represent buildings from downtown Salt Lake City. The chief difficulty with this coupled system is the difference in scales between the two models. Although one could nest further with COAMPS, the finest (300 m) mesh resolution is still very far away from the 1-10 meter resolution that was used to resolve the buildings in FEM3MP. This implies that coupling the two models is more akin to mesoscale data assimilation than traditional numerical analysis. Traditional mesh refinement methods link coarse and fine domains by refinement ratios of typically less than four. This paper presents four approaches for driving the fine scale model with coarse information. These approaches are efforts to add turbulence information to the boundary conditions of the fine model that is not present in the coarse one.

3. Discussion

FEM3MP was developed by the Urban Dispersion Computational Fluid Dynamics Group (UDCFD) at Lawrence Livermore National Laboratory. It is a massively parallel model, (dynamics described in Gresho and Chan, 1998; parallelism in Stevens et al., 2000), for studying airflow and dispersion in and around large urban areas. It has performed simulations which contain O(100) buildings spread over 4 square kilometers while resolving building features with scale O(1) meter. FEM3MP uses a finite element discretization that allows for the incorporation of most Geographical Information System (GIS) data formats. Through model validations and case studies, FEM3MP has been shown to capture many of the complex features of building-scale flows such as blocking, channeling and flow recirculations; all of which can lead to nonlinear dispersion patterns. The computational capabilities of the model make it possible to efficiently evaluate the boundary condition approaches presented here.

The model has both a Reynold's Averaged Navier-Stokes (RANS) mode and a large Eddy Simulation (LES) mode. The RANS mode parameterizes completely turbulent variation which leave only the mean fields for simulation by the model. It is cleanest method of simulation as it only requires an estimate of turbulent kinetic energy at inflow. The only other information needed to drive the model is a large scale mean wind and possibly its gradient taken from the large scale model. This is approach 1 and is illustrated by Figures 1 and 2.

Unfortunately, RANS is often inadequate as seen in cases where vortex shedding is important. One such case is seen in laboratory experiments involving flow over cubical obstacles. The vortex shedding behind the obstacle causes the plume to be much wider than would have occurred if the obstacle had not been present. For these cases it is necessary to explicitly simulate the turbulent kinetic energy and other variances associated with the flow. This motivates our other three approaches that provide synthetic turbulence information for the inflow boundary condition. The simplest alteration to Approach 1 (Approach 2) is to add a random component to the inflow velocity. Given a long fetch, it is possible that enough turbulence could be internally generated to eliminate the need for explicit turbulence data at the inlet. Approach 3 tries to reduce this computationally expensive fetch by synthetically generating dynamically consistent eddies via additional LES fields to superimpose on the mean inflow. This requires an additional LES such as a channel flow with a flat horizontal lower boundary and periodic boundary conditions. The winds would be driven via a nudging technique that is similar to imposing a large scale mean pressure gradient. Ideally, the additional calculation would be less expensive than the fetch needed for Approach 2. Approach 4 is mainly for diagnostic purposes and replaces all the lateral boundaries by periodic ones. While this adds complications, the turbulence at the boundaries in this approach is generated in a consistent manner without any contamination from the coarse simulation.

At the conference, these approaches will be further explained and compared to determine their effectiveness in improving the accuracy of the coupled COAMPS-FEM3MP modeling system.

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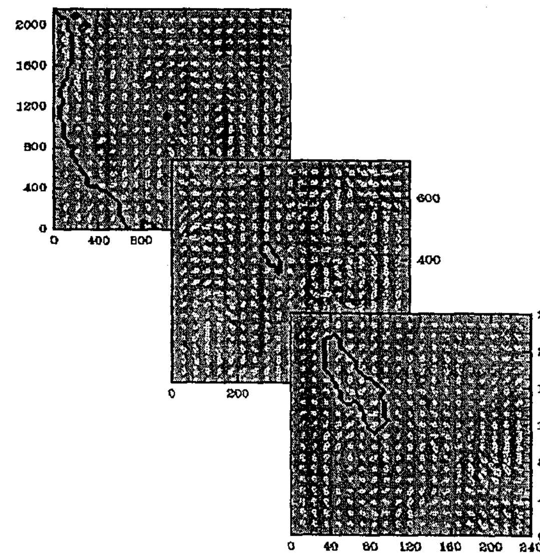

Figure 1: Illustration of COAMPS triple nest. The coarsest mesh is at top and the finest at bottom. The colormap is the height of the topography and the white lines are velocity vectors.

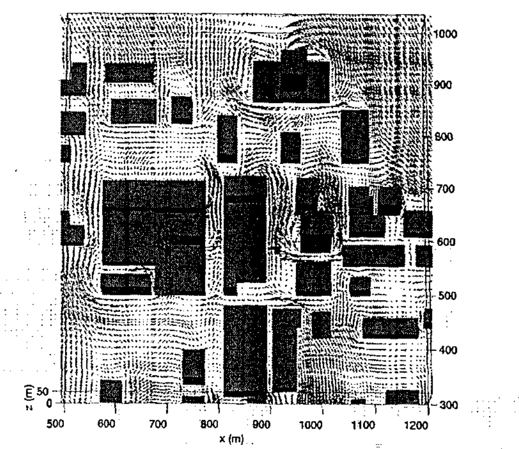

Figure 2: Flow field realization of Downtown Salt Lake

4. References

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